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Ceramic membranes that transport ions play an essential role in numerous energy conversion systems, including solid-state Li-ion batteries, proton and oxygen separation membranes, intermediate-temperature solid oxide fuel cells and solid oxide electrolysis cells,¹ and partial oxidation of methane for natural gas processing.² The operation of membranes in realistic operating scenarios may lead to changes in the phase formation, interfacial characteristics, and microstructure of material systems, thus affecting performance. With decreasing thickness of membranes aimed at enhanced transport, surface and interfacial effects become more important and can dramatically impact membrane performance.

The purpose of this themed collection is to provide a snapshot of current research in the field and highlight challenges and opportunities. The use of ceramic-based ion conducting membranes for a wide range of applications in energy conversion and storage is a challenging task; however, the research outlined in this collection contributes to an improved understanding of the fundamentals and new materials opportunities and approaches, while providing

Introduction to 'Conducting ceramic membranes for energy conversion and storage'

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concurrent opportunities for early-career researchers to publish alongside established leaders in the field. This themed collection consists of 12 papers addressing the following primary topics:

- Li-based solid state batteries.
- Beyond Li conductors (Na, K).

- Protonic ceramic reversible fuel cells: electrolyte and anode/cathode electrode and catalyst design, cell components, cell design, reversible and dynamic operation, and testing.

- Oxygen-ion fuel cells and electrolysis cells, cell components, cell design,



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Kyle Brinkman is the chair of the Department of Materials Science and Engineering at Clemson University in Clemson, SC. Kyle is a two-time Clemson graduate (BS Chemical Engineering 1998 and Materials Science and Engineering 2000) who returned to Clemson in 2014 after a global research career. He graduated from the Swiss Federal Institute of Technology in Lausanne, Switzerland, with a PhD in materials science and engineering. Brinkman then served as a postdoctoral fellow at the Advanced Industrial Science and Technology Institute in Japan as part of a program sponsored by the Japanese Society for the Promotion of Science and later worked as a principal engineer in the Science and Technology Directorate of the U.S.

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reversible and dynamic operation, and testing.

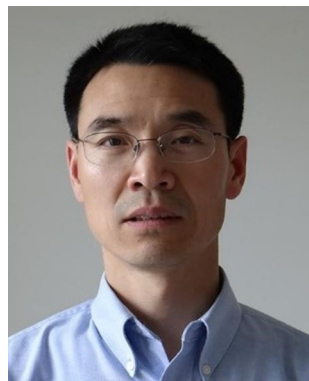
- Ceramic-based oxygen and hydrogen separation membranes and membrane systems for natural gas processing and upgrading.
- Computational materials science of ceramic ionic conductors.

Highlights include work by Sun *et al.* (<https://doi.org/10.1039/d2ma01003h>), who present a review linking structure with ionic conduction mechanisms for solid-state proton and hydride anion materials.

Zheng *et al.* (<https://doi.org/10.1039/d3ma01167d>) examine a triple oxygen,

proton and electron conducting candidate material, $\text{PrNi}_{0.7}\text{Co}_{0.3}\text{O}_3$, under dynamic operating conditions to investigate the degradation behaviors *via* novel accelerated stress testing.

Sozal *et al.* (<https://doi.org/10.1039/d3ma00793f>) fabricated patterned Ag electrodes on BZCYb4411 proton-conducting



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electrolyte by photolithography and E-beam evaporation to characterize interfacial properties, leading to improved intermediate-temperature proton ceramic fuel cells (IT-PCFC).

Ishii *et al.* (<https://doi.org/10.1039/d3ma00901g>) present an alternative use of the popular solid-state ceramic-based Li-ion conductor LLZO as a potential proton-conducting solid-state electrolyte for fuel cells and electrolyzers.

Rowberg *et al.* (<https://doi.org/10.1039/d3ma00308f>) use computational methods to demonstrate that high ionic conductivity can be achieved through optimizing synthesis conditions to maximize the concentrations of interstitial protons in conventional BaZrO₃ and BaCeO₃ proton-conducting materials systems.

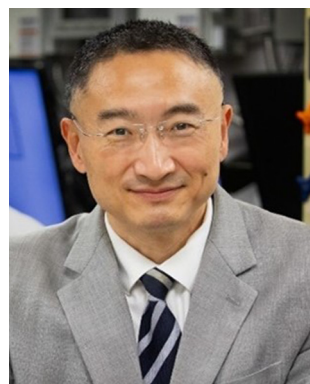
Fischer *et al.* (<https://doi.org/10.1039/d3ma01095c>) discuss work on a dual-phase composite 60 wt% Ce_{0.8}Gd_{0.2}O_{2-d}-40 wt% FeCo₂O₄ (60CGO20-FCO) oxygen transport membrane (OTM) with demonstrated high levels of oxygen permeability. They discuss the stability and oxygen permeance related to mechanically and chemically stable compositions and an optimized microstructure.

We appreciate all authors for their submissions and interest in the themed collection and the reviewers for their comments and suggestions. We would like to thank the editorial staff of the Royal Society of Chemistry (RSC) for assistance putting together this themed collection and hope that the reader will enjoy this collection of articles highlighting current trends in the

field of conducting ceramic membranes for energy conversion and storage.

References

- 1 P. S. Gaikwad, K. Mondal, Y. K. Shin, A. C. T. van Duin and G. Pawar, *npj Comput. Mater.*, 2023, **9**, 149.
- 2 G. Chen, A. Feldhoff, A. Weidenkaff, C. Li, S. Liu, X. Zhu, J. Sunarso, K. Huang, X.-Y. Wu, A. F. Ghoniem, W. Yang, J. Xue, H. Wang, Z. Shao, J. H. Duffy, K. S. Brinkman, X. Tan, Y. Zhang, H. Jiang, R. Costa, K. A. Friedrich and R. Kriegel, *Adv. Funct. Mater.*, 2022, **32**, 2105702.



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materials and interfaces for energy systems, including batteries, fuel cells, and electrolyzers.

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